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(6) RELIABILITY IN GUIDED MISSILE SYSTEMS ,

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RELIABILITY IN GUIDED MISSILE SYSTEMS

Introduction

Modern warfare demands the most advanced weapons which science and technology can produce. Yet the development and performance of these new weapons, with their great complexity, has focussed nation wide attention on the increasingly critical and urgent problem of reliability.

The high rate of failure in military electronic equipment, due to highly complicated nature of the problems involved, is particularly serious. To deal with this problem the Research and Development Board in the Department of Defense established last year an Ad Hoc Group on Reliability of Electronic Equipment. An extensive survey (Ref. 1) of the problem resulted in (1) a progress report embodying far-reaching conclusions and recommendations, (2) a continuing RDB Electronic Reliability activity, and (3) a directive from the Secretary of Defense to the three Services stating that "Reliability must be a prime objective in all phases of the procurement and use of electronic equipment, beginning with the establishment of military characteristics and including operational training, maintenance, organization and facilities, as well the quality of the equipment".

In the field of guided missiles the reliability problem is particularly acute. It is acute partly because the whole technology of missiles is new, and also because of the novel and complex mechanical and electronic devices which must operate under severe environmental conditions. Thus the missile reliability problem includes the entire problem of electronic reliability in an exaggerated form. Reliability has been a familiar problem in missile testing activities during the last five years, and with the recent acceleration of the guided missile program it becomes important to focus attention on the problem of reliability in order to insure a successful national effort in the field of guided missiles.

The purpose of this paper is to discuss the technical problem of reliability in guided missile systems, is discussed.

Statement of the Problem:

Let us begin by stating the problem. Guided missiles involve the use of a multiplicity of electrical, mechanical, and electro-mechanical devices under very severe conditions. All of these components must operate during the time the missile is in the air. In addition, before and during the flight phase an organization of men and machines must also perform properly on the ground, on shipboard or in aircraft. And finally, a complex man-machine support system must function properly in development, production, supply, testing, and maintenance, to insure the desired operation of the guided missile system. The problem is to achieve and maintain optimum reliability in guided missile systems, including both men and machines.

Several terms in this statement need emphasis. First, the objective is to achieve and maintain reliability, so that reliability is a problem throughout the service life of the missile, and is not merely a matter of "debugging" the bird and system during its development. Second, "reliability" means probability of success; more specifically, the reliability of a given component or system is the probability that it will perform its required function under operational conditions for a specified operating time. As an example consider a rocket motor. One of its performance parameters is the thrust. Suppose that for successful motor performance the thrust must lie within certain limits for a specified time. These performance limits, together with the required operating time, define the task, that is, the performance requirements. A motor whose thrust lies within the task limits for the required time is successful; one whose thrust falls outside the limits during performance fails.

The distribution of performances can be established by measuring the thrust of a number of motors. Most of the thrust values will lie inside the task limits,

initially. During the operating time, however, some of them will drift outside and the performance distribution function broadens. At the end of the operating period a certain fraction of the motors will still have thrusts within the task limits. This fraction is the probability that a motor will perform within the task limits during the operating period, and is numerically equal to the reliability.

Similar remarks hold for the remaining performance parameters of the motor. In general the performance distribution will thus include all the operating characteristics necessary to determine the state of the system for the purpose at hand, and in the same way the task will include all the performance limits, so that each performance parameter in the performance distribution is matched by performance limits in the task. The reliability of the system is then the probability that all the performance parameters lie within their task limits for the duration of the operating period.

It is important to note that the reliability depends not only on the spread of the system performances (which is affected by the environment) but also on the task and the operating time. In general the reliability of a system is decreased if the task limits are narrowed or if the operating time is increased. The reliability also tends to be lowered if the performance spread is broadened, either through less quality control or through increased environmental severity. For example, in a guidance system, high temperatures in flight may broaden the spread in electron tube performance far beyond that found under laboratory conditions, with a consequent decrease in guidance reliability.

In the case of missiles it is convenient to exclude from reliability those failures caused by direct enemy action and to treat them separately under vulnerability.

Reliability may be split further into so-called aborts and "inaccurates". Aborts are failures which result in drastic, unusual, and unexpected performances

lying far outside the normal performance spread. This normal spread is then considered under accuracy, and reliability becomes the probability that the missile will not abort. This split of reliability into accuracy and non-abort probability is useful in some cases but is artificial, since many marginal failures in the components (in the guidance, for example) may result in missile aborts. Thus system accuracy and reliability are interrelated by the marginal performance of components.

Why is the Problem Difficult?

Now let us see why the reliability problem is difficult. Improving reliability is of course part of the development, production and use of any new technological device. For relatively simple systems there is a definite period of "debugging" in which the faults are easy to detect and eliminate, and the reliability problem is solved. In large systems, however, the problems of finding and curing the ailments increase rapidly with complexity and require a more scientific approach, which I shall call reliability control and shall discuss briefly later in the paper.

Guided missiles are at the forefront of modern science and technology and missile engineering requires the integration of new fields of aerodynamics, propulsion, servo-mechanics, and electronics. In addition, the whole missile industry is going through growing pains under the impetus of the present accelerated programs. These are all general reasons why reliability is a problem in guided missiles, and they are common to other weapons as well.

In addition, there are six technical factors which make the reliability problem particularly serious in guided missiles:

(1) Complexity: The first of these is complexity. Modern guided missile systems are extremely complex in terms of both the number of parts in the structure and also in terms of their many interactions in functions.

This high degree of complexity tends to increase the chances of failure. For a missile with 50 components in series, each with a reliability of 99 percent, the overall reliability is only 60 percent. For a system of 300 such components the probability of success is only 5 percent! In piloted aircraft an abort rate of about five percent is generally considered acceptable (Ref. 2). If atomic-warhead-carrying missiles were involved, this rate would mean "throwing away" five percent of the atomic missile stockpile, since the warhead can rarely be recovered from a missile which really "aborts" (Ref. 2). Nevertheless, let us use the figure of five percent aborts to see what the average component reliability would have to be. If the missile were considered to consist of five components (e.g., motor, control system, guidance system, fuze, and warhead), the failure rate of each would have to be only one percent. If the missile were broken into 50 smaller components, the failure rate would have to be only one-tenth of one percent, in other words the average component reliability would have to be 99.9 percent! The moral to be drawn from these complexity arguments is simple: The failure rate of the major components of a missile system must be at least an order of magnitude smaller than the failure rate of the missile itself, while the failure rate of the many parts (such as motors, vacuum tubes, valves, etc.) must be several orders of magnitude smaller than the failure rate of the missile.

(2) Lack of Component Redundancy: The second difficulty in building reliable missiles is the lack of component redundancy. Most of the components of a missile system are in series, in the sense that any failure of a component fails the missile. Considering the components as links in the chain comprising the missile, it is clear that the chain is literally no stronger than its weakest link: the system cannot be more reliable than its least reliable component. This is in strong contrast to a piloted aircraft, for

example, where the probability of failure is greatly reduced through redundancy by having standby components and a copilot, that is, by having parallel links in the chain.

(3) Lack of Feedback: The third factor is the lack of feedback of good failure data. In order to detect and cure failures it is necessary to determine the cause of failure. This is not an easy task even in ordinary engineering work where direct inspection and instrumentation is possible during the operation. In missiles it is a far more difficult problem because the feedback of information on failures occurring during flight is very inadequate, especially under operational conditions, and in most cases the missile is not recoverable for an autopsy. This means that many test flights are necessary, with much expensive telemetering instrumentation to monitor the operation of the components.

(4) Severe Environments: The fourth factor concerns environmental conditions. There is little good data on many of the environmental stresses in shock and vibration, temperature, pressure, and humidity which the missile must withstand in transportation, handling, launching, and flight, and some of these stresses are known to be very severe. For example, a Signal Corps report recommends that to simulate typical field handling conditions, electronic equipment should be tested by dropping it 5 feet onto soil or concrete, during which it will suffer from 200 to 500 g's acceleration for several milliseconds. Without good environmental data it is difficult either to design adequate safety margins into the components or to perform realistic environmental tests.

(5) Weight and Space Requirements: The fifth factor involves weight and space requirements, which impose severe limitations on the design and packaging of components; these factors, together with the high performance required of the components, result in small safety margins against failure.

This is particularly important in the electronic equipment, where low weight factors favor fragile mechanical construction and the small space available makes it difficult to design for adequate cooling and accessibility.

(6) Electronic Reliability: The sixth factor is electronic reliability. Missile performance and reliability is critically dependent on the electronic equipment of the guidance and control functions. It is well known that the reliability of military electronic equipment is low; for example, it is estimated that only about one-third of the Navy's shipboard electronic gear is operating properly (Ref. 1). This is particularly true for those missile systems in which the major part of the guidance equipment is airborne in the missile itself. In general it appears that electronic reliability is the most important part of the missile reliability problem. Indeed, Major General Putt of the USAF Research and Development Command recently stated that "the scheduled introduction of guided missiles into operational units depends primarily on the accuracy and reliability of guidance and control systems" (Ref. 2).

In view of these six factors it is abundantly clear that the problem of achieving and maintaining reliability in guided missile systems is important and difficult. It is a serious challenge to both the Armed Services and the industry.

The V-2 Reliability

A brief review of the German V-2 history will help to set the problem in historical perspective. The first experimental work at Peenemunde began in 1933 with the A-1 rocket weighing 150 kg, and was followed in 1934 by the A-2 which reached a height of 2000 m. As early as 1935 German authorities gave serious consideration to the military applications of rockets. Basic research had begun

several years earlier and much effort was put into this field. As a result there was a base of industrial support for missile designers. Rocket motors and fuels were commercially available and during the next few years a series of high-speed windtunnels and jet engine test stands were built. From 1936 to 1942 about 500 million dollars was spent in developing the Peenemunde Rocket Center; by 1942 nearly 6000 people were employed, about 2000 of whom were scientists and engineers (Ref. 3). This program involved more than a third of Germany's entire aerodynamic research. In 1938 the first experiments were made with the A-3 and later with the A-5. These were small scale V-2's about 25 feet long, weighing 800 kg. Many of these A-3's and A-5's were fired and gave valuable experience and technical data.

In 1940 work was begun on the V-2 and on July 6, 1942, the first V-2 was fired. It rose precisely 3 feet off the ground and then exploded with enormous violence, destroying the test station. Numbers 2 and 3 also exploded but at 16,000 feet. Finally, number 4 was a success; in October 1942 it covered a distance of 170 miles. Number 5, fired a short time later, was also a success, but the next 13 were failures. Thus out of the first eighteen rockets only two performed successfully, giving a reliability of 11 percent. During the three years of development, testing, and training, some 3000 V-2's were fired. Problem after problem arose in the motor, the airframe, and the control system. For example, it was found that of the rockets which were launched successfully, about half broke up in the air, and a large scale theoretical and experimental study involving about 300 V-2 launchings was required to solve the airburst problem, which turned out to be caused by an aerodynamic deficiency. In all, some 62,000 changes were made during the production of the V-2, which consisted of about 30,000 different construction and engine parts. Finally, in September 1944, ten years after the first test rocket firings at Peenemunde, the first V-2 was fired against London. By April, 1945, when the V-2 campaign ended, about 2700 V-2's

had been fired against London and Antwerp, with a reliability of 75 or 80 percent and an accuracy much lower than was called for in the military plans (Ref. 5).

After the war a number of V-2's were captured and taken to White Sands for tests (Ref. 6). During the five-year program 68 V-2's were fired, of which 32 were successful. Of the 36 failures, 23 occurred during launching and the remaining 13 were evenly divided between motor and steering malfunctions. Thus the reliability during the American V-2 firings was 47 percent as compared with the German combat reliability of 75 percent. This well illustrates the difficulty of obtaining a high reliability; even with Germain experience and technical personnel more than half the missiles failed in the American tests. In view of my remarks concerning the difficulty of determining cause of failure from flight tests, it is of interest to note that of the 36 V-2 failures, in only 6 cases was the <u>cause</u> of failure established; in 14 cases it was known <u>what</u> failed but not <u>why</u>; for the remaining 16 cases only the general <u>area</u> of failure was known. Thus in only 1/6 of the failures was the cause of failure ascertained, so that the failed component could be immediately improved. While the sample is too small to draw general conclusions, it indicates the high price paid for failure information in missile test flights.

<u>Achieving and Maintaining Reliability:</u>

Let us return to the problem of achieving reliability. The objective of a missile project is to develop a producible and reliable missile. Until performance capability has been demonstrated reliability is secondary in importance; when the required capability has been demonstrated, however, reliability becomes of primary importance, and unless an adequate combat reliability is achieved the missile is ineffective as a military weapon. The improvement of system reliability is therefore a vital phase of any weapon development.

The reliability of a missile system can be improved in four fundamental ways:

(1) <u>By improved components</u>: The use of more reliable components is the usual way to increase system reliability and offers the only long-term way of making large improvements in reliability.

(2) <u>By improved design</u>: Improved system and component design may increase reliability by decreasing complexity, increasing safety margins against failure, and improving maintenance and operator effectiveness. The opportunities for increasing reliability by improving design appear particularly hopeful for electronic equipment in missile systems.

(3) <u>By improved selection and training of personnel and standard operating procedures</u>: Reliability can be increased by improving the quality and effectiveness of the skilled personnel, both military and civilian, who are required in the assembly, inspection, packaging, handling, testing, maintenance, and operation of guided missiles.

(4) <u>By component redundancy</u>: The use of standby components in case of failure increases reliability, provided the switching or decision device is reliable. The method may be costly (in dollars and weight, for example) but may be justified. Most important, it does not require improved components. For example, suppose the guidance system has a reliability of 75 percent, or a failure rate of one-fourth. Now replace the single system by two of these guidance systems in parallel, so that if one fails the other takes over. For missile failure to occur it is now necessary that both guidance systems fail, so that the failure probability is 1/4 times 1/4, or 1/16 or 6 percent. Hence the reliability is 94 percent, a significant increase over the original 75 percent.

In order to make these improvements in all the various phases of missile development it is necessary to obtain technical information on failures. More

specifically, statistical data is required on the number of failures, the identity of the failed components, the time to failure, and the causes of failure. Statistical information of this type is costly and difficult to obtain from test flights; the most hopeful approaches seem to lie in the use of recoverable missiles and in simulation tests in which the missile is subjected to environmental conditions experienced in shipping and handling, in launching, and in flight. Shock and vibration conditions are important potential sources of failure in all phases. In order to determine a realistic mixture of environmental stresses for testing, good data are needed on the shock and vibration, temperature, pressure, and humidity experienced by an actual missile in traveling from the factory to the target. Unless good environmental data are obtained there is the danger that missiles and their components will be designed to survive the simulation test environments rather than the actual operational environment. In addition, since there is always a variety of failure causes, a statistical approach is necessary to insure that the defects are cured systematically in order of their importance rather than in the order of their accidental appearance in tests.

Finally, having achieved and demonstrated an adequate reliability to justify service acceptance, the missile system is put into production and service use, and the problem of <u>maintaining</u> the reliability becomes vital. This requires a failure-monitoring activity, similar to quality control. Continuous and rapid reports on failures are needed to evaluate the reliability and insure that it lies within acceptable limits. Failures in transit, handling, storage, testing, and operational use should be analyzed to detect and eliminate sources of trouble.

<u>System Reliability Control, the Analogue of Component Quality Control</u>:

How should all these technical activities be efficiently coordinated? In a simple device reliability is achieved by recognizing faults when they occur and eliminating them. In a complex guided missile system this simple approach

is correct in principle but costly and time-consuming in practice. As in any scientific or engineering project, it is therefore necessary to organize and direct the technical effort required to solve the reliability problem in sy.. s. This organized systems activity will be called reliability control; it is the systems analogue to component quality control, used to maintain quality in manufactured components. More exactly, by reliability control I mean the coordination and direction of technical reliability activities through scientific planning from a systems point of view.

Reliability control consists of the following cycle of five steps:

(1) Determination of Requirements: Reliability requirements must be established for the system and its components. From the definition of reliability this demands specification of the required performance limits, the operating time, and the environment, as well as the required reliability.

(2) Collection of Data: Reliability data on component and system failures and their causes must be collected in statistically significant amounts.

(3) Analysis: The data must be analyzed to determine whether the requirements are met, to establish the most important causes of failure, and to recommend methods of improvement.

(4) Improvement: Action must be taken to remove the most important defects and reduce the failure rate to the required level.

(5) Surveillance: A continuous and critical surveillance of the system must be carried out to insure that the "improvements" actually reduce the failures, to anticipate and examine new and unsuspected sources of failure, and to review and modify requirements.

There is no sharp distinction between reliability control and the usual engineering methods of improving reliability. Nevertheless it is important to recognize that reliability control differs in degree from conventional engineering

in three respects: first, overall system planning is emphasized; second, statistical analysis of failure data is used as a control; and third, constant surveillance of the system through feedback of failure data is required in all phases of development and production.

In conclusion I would like to emphasize three points:

First, reliability of the hardware in a missile system is fundamentally the result of engineering which takes into account realistically and from a systems point of view all the significant factors affecting the performance of the weapon.

Second, reliability is a difficult and important technical problem which requires careful planning, a large effort, and great attention to details.

Third, reliability and the associated problem of accuracy are the primary factors governing the time at which guided missile systems will become operational. Without adequate attention to reliability, both on the part of the using Services and the contractors, these operational dates will be delayed.

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